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14. ABSTRACT
In this project, we carried significant amount of research innovation in wireless networking resource allocation, including the following: (1) the 3D tradeoff analysis provides a systematic an fair comparison of a variety of wireless scheduling algorithms in mobile ad hoc wireless networks, (2) the adaptive CSMA algorithm is the first utility optimal random access algorithm practically implemented on off the shelf commodity WiFi dirvers, (3) new mathematical methods in stochastic approximation theory were developed in the process of proving utility optimal of the adaptive CSMA algorithm, (4) the first implementation and demonstration of optimal CSMA on wireless devices. It has lead to a large number of publications and the start of a tech transfer into DoD applications.

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Distributed Scheduling in MANET

Final Report

1 Project Participants at Princeton

1.1 Principal Investigators

Mung Chiang, Princeton University

1.2 Post-Doctoral Researchers

Dr. Hongseok Kim
Dr. Amitabha Ghosh

1.3 Ph.D. Students

Tian Lan
Yiannis Kamitsos

1.4 Collaborators and Organizational Partners

Collaboration with Qualcomm, Motorola, and Microsoft.

2 Activities and Findings

2.1 Summary

1. The 3D tradeoff analysis provides a systematic an fair comparison of a variety of wireless scheduling algorithms in mobile ad hoc wireless networks.
2. The adaptive CSMA algorithm is the first utility optimal random access algorithm practically implemented on off the shelf commodity WiFi dirvers.
3. New mathematical methods in stochastic approximation theory were developed in the process of proving utility optimal of the adaptive CSMA algorithm.

4. The first implementation and demonstration of optimal CSMA on wireless devices.

2.2 Major Research Activities

The following results have been presented in multiple plenary and keynote speeches given by the PI, including those at IEEE INFOCOM, IEEE GLOBECOM, IEEE WiOpt, KU Leuven Simon Steven Lecture, and MIT LIDS Student Conference.

In an interference environment like wireless cellular or ad hoc networks, scheduling controls which link can transmit at each time slot and has been extensively studied since the 1960s. After the 1992 paper on maximum weight scheduling by Tassiulas and Ephremides, the research community has been developing simpler and more distributed scheduling algorithms that can still perform well in terms of throughput and delay.

In an ACM Mobihoc paper, we developed the first unifying framework of throughput-delay-complexity 3 dimensional tradeoff. Each scheduling algorithm is represented as a point in the 3D tradeoff space, and achievable tradeoff curves are extended through various parameterizations. This provides the first systematic way to compare a variety of scheduling algorithms in a fair way. Then in an ACM Mobihoc 2009 paper, we further developed the technique of heavy traffic approximation for wireless scheduling's delay performance characterization. By proving the so called state space collapse property, we can reduce the dimensionality of the problem from L links to 1 "representative" link. We showed that under heavy load and communication overhead in the scheduling algorithms, delay increases exponentially as the network grows.

Furthermore, in collaboration with Microsoft Research in UK, we were among the three teams that developed the first adaptive CSMA algorithm that can approach utility optimality arbitrarily tightly without using any explicit message passing. Each node can learn the interference environment purely based on the observed service rate in the past. Proving this result required substantial innovation in the mathematics of stochastic approximation theory and distributed optimization algorithm. This result also lead to new discoveries on transient behaviors of adaptive CSMA, such as the tradeoff between long-term efficiency and short-term fairness among the interferring links.

Then in a paper to appear in IEEE INFOCOM 2011, together with my former postdoc (now faculty at KAIST Korea) Yung Yi and collaborator Ed Knightly at Rice, we reported the first ever *experimental implementation* of optimal CSMA. We successfully implemented the theory inspired design onto conventional 802.11 drivers, offering a feasible path towards deployment. We also demonstrated the predictive power of theory, while discovering the gaps between theory and practice.

This further leads to a redesign by our team that bridged these gaps successfully. In 2012, we completed the first ever systems implementation of the redesigned optimal CSMA. This became the first demonstrated design that can provide near-optimal throughput in all key atomic topologies, including hidden nodes, information asymmetry, and flow in the middle. This success of bridging theory and practice has been documented in a submission to ACM CoNEXT conference recently. It has also started tech transfer path towards tactical military networks, as a defense contractor IAI has implemented it on their large scale wireless

emulation system and reproduced the results independently.

More generally, for high-dimensional, non-convex resource allocation problems in wireless networks, there is the practically important question of implementable and suboptimal algorithms. Protocol components in the current network architecture are often designed to attain certain optimality goals, with the hope that, when these optimal components work together, the overall network performance will also be optimized. However, for many network settings, due to either the scale of the network; the constraint on the response time of the algorithms; or the inherent non-convexity in the system, such optimal solutions can be difficult to attain. We have been exploring architectural choices that are robust to sub-optimality in each individual component. We argue that there is a need to shift our attention from optimal but complicated solutions, to easily implementable designs that are suboptimal but still possess good performance bounds. We studied the rate-allocation component of the network architecture, and investigated the following questions related to suboptimal components. (1) We investigated the robustness of the network architecture by studying how much sub-optimality the rate-allocation component can exhibit while the overall network architecture can still achieve satisfactory user-level performance. (2) We investigated how to tradeoff suboptimal rate-allocation with other performance measures, e.g., throughput and link utilization.

Our findings in a paper apppeared in IEEE/ACM Transactions on Networking demonstrate that it is possible to design an overall network architecture that is robust to suboptimal components. In particular, we show that even when the transport layer only computes suboptimal rate allocation, under suitable conditions the system can still achieve good user-level performance (in terms of achieving the largest connection-level stability region). Specifically, when the ratio of the utility gap (caused by a suboptimal rate allocation algorithm) to the maximum utility approaches zero as queue length tends to infinity, the maximum connection-level stability region can be retained. When the utility gap is in proportion to the maximum utility, only a reduced stability region can be achieved, in which case we provide a lower bound for the achievable stability regions. Not only that these results demonstrate how to characterize and design network architectures that are robust to suboptimal (but potentially simpler and easier-to-implement) rate-control, they also allow the network designer to intentionally under-optimize a given design objective, with the goal to improve other performance measures of the network.

2.3 Training and Development

Post-doc Hongseok Kim joined Bell Labs as a member of the technical staff. Graduate student Tian Lan graduated in 2010 and joined George Washington University as a tenure track Assistant Professor.

2.4 Outreach Activities

The subject of wireless scheduling was recently given as a keynote speech at IEEE WiOpt Conference in Seoul, Korea, by Chiang. Chiang has given numerous talks on architectures for wireless networks, especially on interference management and distributed scheduling,

to outline the intellectual challenges and engage the larger community in these promising research directions.

The first EDGE Lab Open House was held in April 2011 with a large number of participants from across the communities and networking industry, including a highlight on scheduling in MANET.

3 Publications

3.1 Journal Papers

L. Yang, H. Kim, J. Zhang, M. Chiang, and C. W. Tan, "Pricing based decentralized spectrum access control in cognitive radio networks," To appear in *IEEE Transactions on Networking*, 2012.

S. Sorroshyari, C. W. Tan, and M. Chiang, "Power control for cognitive radio networks," To appear in *IEEE/ACM Transactions on Networking*, 2012.

T. Lan, X. Lin, M. Chiang and R. Lee, "How Bad Is Suboptimal Rate Allocation?" *IEEE/ACM Transactions on Networking*, vol. 19, no. 4, pp. 1194-1207, June 2011.

W. Zhang, U. Mitra, and M. Chiang, "Optimization of amplify-and-forward multicarrier two-hop transmission," *IEEE Transactions on Communications*, vol. 59, no. 5, pp. 1434-1445, May 2011.

J. Liu, Y. Yi, A. Proutiere, M. Chiang, and H. V. Poor, "Convergence and tradeoff of utility-optimal CSMA" (Invited Paper), *Wiley Journal of Wireless Communications and Mobile Computing, Special Issue on Advances in Wireless Communications and Networking*, vol. 10, no. 1, pp. 115-128, January 2010.

H. Mohsenian Rad, J. Huang, M. Chiang, and V. Wong, "Utility optimal random access: Reduced complexity, fast convergence, and robust performance", *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 898-911, February 2009.

H. Mohsenian Rad, J. Huang, M. Chiang, and V. Wong, "Utility optimal random access without message passing", *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1073-1079, March 2009.

Jiayue He, Jennifer Rexford, and Mung Chiang, "Design for optimizability: Traffic management of a future Internet," a chapter in the book *Algorithms for Next Generation Architectures*, 2012.

3.2 Conference Papers

J. Lee, K. Lee, Y. Yi, S. Chong, B. Nardelli, E. Knightly, and M. Chiang, "Making CSMA optimal," Submitted to *ACM CoNEXT*, 2012.

B. Nardelli, J. Lee, K. Lee, Y. Yi, S. Chong, E. Knightly, and M. Chiang, "Experiment evaluation of optimal CSMA", *Proc. IEEE INFOCOM*, Shanghai, China, April 2011.

L. Fu, H. Kim, M. Chiang, J. Huang, S. Liew, "Energy conservation and interference mitigation: From decoupling property to win-win strategy", *Proc. IEEE CDC*, Atlanta, GA, December 2010.

Yung Yi, Alexandre Proutiere, and Mung Chiang, "Complexity of wireless scheduling: Impact and tradeoffs", *Proc. ACM Mobihoc*, Hong Kong, China, May 2008.

Yung Yi, Junshan Zhang, and Mung Chiang, "Effective throughput and delay in wireless scheduling: Vacation model for complexity", *Proc. ACM Mobihoc*, New Orleans, LA, May 2009.

Wenjie Jiang, Rui Zhang-Shen, Jennifer Rexford, and Mung Chiang, "Cooperative content distribution and traffic engineering in an ISP network," in *Proc. ACM SIGMETRICS*, June 2009.

Jiayue He, Rui Zhang-Shen, Ying Li, Cheng-Yen Lee, Jennifer Rexford, and Mung Chiang, "DaVinci: Dynamically Adaptive Virtual Networks for a Customized Internet," in *Proc. ACM SIGCOMM CoNext Conference*, December 2008.

S. Liu, R. Zhang-Shen, W. Jiang, J. Rexford, and M. Chiang, "Performance bounds for peer-assisted live streaming", *Proc. ACM Sigmetrics*, Annapolis, MD, June 2008.

D. Xu, M. Chiang, and J. Rexford, "Link-state routing with hop-by-hop forwarding can achieve optimal traffic engineering", *Proc. IEEE INFOCOM*, Phoenix, AZ, April 2008.

3.3 Invited Presentations

Institute of Pure and Applied Mathematics Workshop on Network of Networks, "Content-Pipe Divide", November 2008.

Institute of Pure and Applied Mathematics Workshop on Mathematical Frontiers of Networking Research, "Distributed Scheduling", November 2008.

UCLA EE Department Seminar, "Two Open Problems in Networking: Random Access Performance and P2P Streaming Capacity", December 2008.

University of Toronto Networking Research Seminar, "Wireless Scheduling", April 2009.
Microsoft Research Seminar, "Wireless Scheduling", June 2009.

KAIST Information Science Seminar, "The Content-Pipe Divide", June 2009.

IEEE WiOpt Plenary Speech, “Wireless Scheduling”, June 2009.

IEEE ICME Workshop on Emerging Technologies for Multimedia Communications Keynote Speech, “The Content-Pipe Divide”, June 2009.

MIT LIDS Student Conference, An Axiomatic Theory of Fairness, January 2010.

IEEE INFOCOM Plenary Panel, What is Good Research in Network Theory, March 2010.

K. U. Leuven 15th Simon Stevin Lecture on Optimization and Engineering, Optimization in Networking, July 2010.

Telcordia Annual Strategic Research Review Keynote Speaker, Optimization in Networking, July 2010.

10th International Symposium on Modeling and Optimization (MOPTA) Plenary Speech, ”Optimization in Networking”, August 2010.

Stanford ISL Colloquium, An Axiomatic Theory of Fairness, October 2010.

Caltech IST Lunch Bunch Talk, An Axiomatic Theory of Fairness, October 2010.

Caltech EE Seminar, Can Random Access Be Optimal?, October 2010.

U. Delaware EE Seminar, Can Random Access Be Optimal?, November 2010.

IPAM Optimization and Engineering Workshop, Optimizers on WiFi-Drivers, December 2010.

AFOSR Complex Network Workshop, Small World Delay, December 2010.

IEEE GLOBECOM Plenary Panel, Content Pipe Divide, December 2010.